

Variability and nature of the binary in the Red Rectangle Nebula ^{*}

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Abstract.

We present new observations of the central binary inside the Red Rectangle nebula. The detection of zinc in the optical spectrum confirms that the peculiar photospheric abundances are due to accretion of circumstellar gas. Grey brightness variations with the orbital period are observed. They are interpreted as being due to the variation of the scattering angle with orbital phase. The small orbital separation of the system is not compatible with previous normal evolution of the primary on the AGB. We point out the similarity of the orbital history of this and other similar systems with those of some close Barium stars and suggest that the nonzero eccentricity of the orbit is the result of tidal interaction with the circumbinary disk.

Key words: Stars: binaries: close ; Stars: evolution : Stars: individual: HD 44179 ; Stars: AGB and post-AGB; dust, extinction

1. Introduction

The Red Rectangle nebula that surrounds the star HD 44179 (Cohen et al. 1975) is famous for the molecular and dusty emission it displays in the red and infrared parts of the spectrum. The central star is a peculiar A-supergiant. A major puzzle is that the infrared-to-optical luminosity of the central object in the Red Rectangle is very high (about 33, Leinert and Haas 1989), despite the fact that the extinction of HD 44179 is not larger than $E(B - V) = 0.4$. This led Rowan-Robinson and Harris (1983) to invoke the presence of an embedded M-giant companion; Leinert and Haas went even further, and argued that HD 44179 is a foreground object. The solution of this puzzle is contained in the observations by Roddier et al. (1995), who showed that the optical flux observed from HD 44179 is entirely scattered light from two lobes located above and below a dusty disk, the star itself being hidden by the disk. There is

then no need to invoke another source than HD 44179 to power the luminosity of the nebula.

Waelkens et al. (1992) have shown that HD 44179 is severely iron-deficient, with $[Fe/H] = -3.3$, that also other metals such as Mg, Si, and Ca are severely underabundant, but that the CNO and S abundances of this star are nearly solar. This star is then clearly of the same nature as the other extremely iron-poor supergiants HR 4049, HD 52961 and BD +39°4926 (Lambert et al. 1988; Waelkens et al. 1991a; Kodaira 1973; Bond 1991), which show the same most peculiar abundance pattern, and two of which (HR 4049 and HD 52961) are also surrounded by circumstellar dust. The location of these other low-gravity stars rather far from the galactic plane strongly suggests that they are not massive supergiants, but evolved low-mass stars, and thus that the central star of the Red Rectangle also is an evolved low-mass star. Moreover, the dust features show clearly that the nebula is carbon-rich, which argues that the star has undergone the third dredge-up typical for late AGB stars. Still, the large amount of circumstellar matter and the low galactic latitude $b = -12^\circ$ may indicate that HD 44179 is somewhat more massive than the other stars of the group. The carbon richness of the circumstellar environment, as well as the high luminosity combined with the high or intermediate galactic latitudes, suggest that these stars are low- or intermediate-mass objects in a post-AGB stage of evolution.

While there is no ground any more to consider HD 44179 as a component of a *wide* binary, Van Winckel et al. (1995) have shown that HD 44179 is a *spectroscopic* binary with an orbital period of about 300 days. Also the other mentioned extremely iron-poor post-AGB stars are binaries with periods of the order of one year.

In this paper we discuss new observations of HD 44179 that were triggered by the similarity of this object with the other peculiar binaries. In Section 2 we report on the determination of the zinc abundance in HD 44179, which confirms that the photospheric peculiarity is due to accretion of circumstellar gas. In Section 3 we discuss the photometric variability of HD 44179; for HR 4049 the brightness and colours vary with orbital phase, as a result of variable circumstellar absorption; in HD 44179 it appears more likely that the observed variability is due to pe-

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^{*}based on observations collected at the European Southern Observatory and at La Palma Observatory

Table 1. Photospheric abundances of the extremely iron-poor post-AGB stars (the zinc abundance for HD 44179 is from the present study, the other values are taken from Van Winckel 1995)

Object	Iras	[Fe/H]	[C/H]	[N/H]	[O/H]	[S/H]	[Mg/H]	[Si/H]	[Zn/H]
HR 4049	10158–2844	-4.8	-0.2	0.0	-0.5	-0.4	?	?	?
HD 52961	07008+1050	-4.8	-0.4	-0.4	-0.6	-1.0	?	?	-1.5
BD +39°4926		-3.3	-0.3	-0.4	-0.1	0.1	-1.5	-1.9	?
HD 44179	06176–1036	-3.3	0.0	0.0	-0.4	-0.3	-2.1	-1.8	-0.6

riodically variable scattering. In Section 4 we discuss the constraints the close-binary nature of HD 44179 imposes on the previous and future evolution of this object.

2. The zinc abundance of HD 44179

In Table 1 we summarize the photospheric composition of the four objects that are known to belong to the group of extremely iron-poor post-AGB stars. These stars are characterized by very low abundances of refractory elements such as Fe, Mg and Si, and about normal abundances of CNO and S. Following a suggestion by Venn and Lambert (1990), Bond (1991) first suggested that the low iron abundances are not primordial, but are due to fractionation onto dust. Indeed, the abundance pattern of these stars follows that of the interstellar gas rather closely.

Convincing evidence for this scenario came from the detection of a rather solar Zn abundance in HD 52961 by Van Winckel et al. (1992): in the photosphere of this star, there is more zinc than iron in absolute numbers! The unusual zinc-to-iron ratio cannot be understood in terms of nucleosynthetic processes, but must be due to the different *chemical* characteristics of both elements, zinc having a much higher condensation temperature than iron (Bond 1992).

From the study of a spectrum of HD 44179 obtained with the Utrecht Echelle Spectrograph at the William Herschel Telescope at La Palma, we can confirm that zinc follows CNO and S also in this star. In Figure 1 we show a spectrum with the 4810 Å zinc line for HD 44179. The zinc abundance derived from this line and the 4722 Å line is $[Zn/H] = -0.6$, while $[Fe/H] = -3.3$. Also in the photosphere of HD 44179 the amount of zinc is near that of iron in absolute numbers. This result further underscores that the central star of the Red Rectangle belongs to the same group of objects as HR 4049, HD 52961 and BD+39°4926. The fact that all four such objects known occur in binaries with similar periods then strengthens the suggestion by Waters et al. (1992) that the chemical separation process occurs in a stationary *circumbinary* disk.

3. Photometric variability

Seen at a high inclination, a circumbinary disk can cause variable circumstellar extinction, because the amount of dust along the line of sight varies with the orbital motion of the star. Such an effect has indeed been observed for HR 4049 (Waelkens et al. 1991b). We have therefore obtained 68 photometric measurements in the Geneva photometric system, with the Geneva photometer attached to the 0.70 Swiss Telescope at La Silla Observatory in Chile, between 1992 and 1996, covering now six orbital cycles. In order to improve on the orbital elements, we have also obtained new radial-velocity measurements with the CES spectrograph fed by the CAT telescope at ESO; the

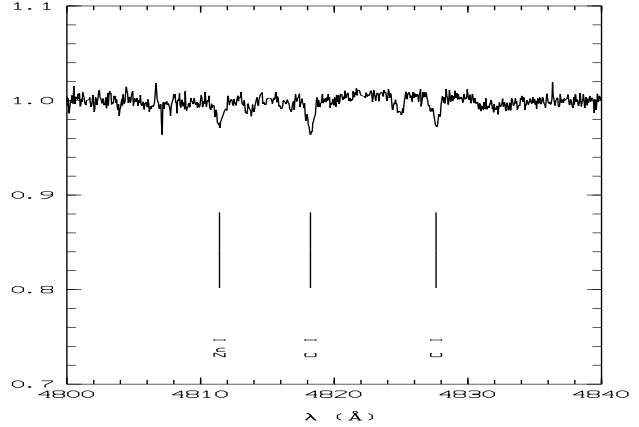


Fig. 1. The observation of a zinc line in the spectrum of HD 44179

data now cover more than five cycles. In Figure 2 we fold the observed visual magnitudes and $[U-B]$ colors with the orbital phase. The orbital period of 318 ± 3 days is somewhat longer as the one determined previously (Van Winckel et al. 1995). The vertical lines on the figure indicate the epochs of inferior and superior conjunction.

It is apparent from Figure 2 that photometric variability occurs with the orbital period. As in the case of HR 4049, minimum brightness occurs at inferior conjunction and maximum brightness at superior conjunction. In the case of HR 4049 the photometric variations are caused by variable obscuration by the circumbinary disk during the orbital motion. This interpretation was confirmed by the colour variations, which are consistent with extinction. However, in the case of HD 44179, *no color variations are observed, not in $[U-B]$, nor in any other color in the optical range.* If variable extinction along the line of sight is responsible for the variability, then the grains causing it must be larger than in HR 4049. On the other hand, many spectral features attest the prominent presence of small grains in the Red Rectangle nebula. We propose that the photometric variability of HD 44179 is not caused by variable extinction, but by the variability around the orbit of the scattering angle of the light that is observed.

The two scattering clouds that are observed cannot be located on the orbital axis of the system, since then no orbital motion would be observed at all! It is much more likely that what we observe is light scattered from the transition region between the optically thick disk and the optical nebula. Roddier et al. (1995) found a smaller opening angle of the inner source (40°) than for the nebula (70°); this can be understood in our model: the scattering angle at the edge of the cone, as seen in projection, is 90° and so probably too large for a significant flux in our direction; the light we observe, must be reflected by

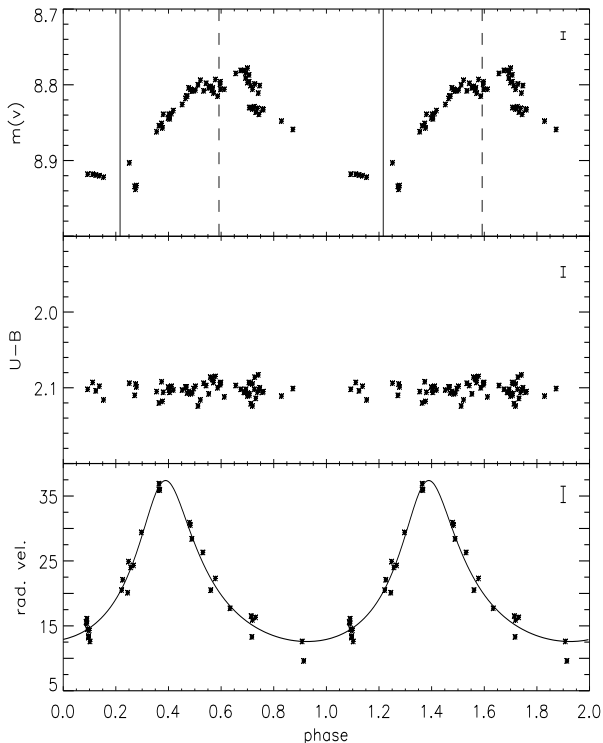


Fig. 2. The phase diagram for the photometric and radial-velocity variations of HD 44179. The phase of inferior(superior) conjunction is marked by a full (dashed) vertical line. Phase 0 corresponds arbitrarily to JD 2448300. A typical error-bar for an individual measurement is shown in the upper-right corner of each panel.

that part of the cone that is directed to us, i.e. where the scattering angle is smallest. In the following, we therefore assume that the inclination at which the orbital motion is observed, is equal to half the opening angle of the cone, i.e. 35° .

Our model is schematically presented in Figure 3. The orbital plane of the binary is nearly edge-on, as is assumed commonly, since the star is hidden and the nebula is remarkably symmetric. The variable scattering angle can be estimated from the size of the orbit and the geometry of the nebula. Roddier et al. (1995) determined that the scattering clouds are located some $0.07''$ above and under the orbital plane. Assuming an absolute magnitude -4.0 for the star we then find from the observed bolometric luminosity and reddening (Leinert & Haas, 1989) a distance of 360 pc, close to the value originally estimated by Cohen et al. (1975) on the basis of different assumptions. This distance then implies that the scattering occurs at a vertical distance of 25 AU from the orbital plane; with an opening angle of the nebula of 70° , it follows that the distance of this region to the orbital axis is some 17.5 AU. From the orbital elements we derive that the radial distance of HD 44179 from the center of mass of the system amounts to 0.53 A.U. at both inferior and superior conjunction, so that the scattering angle of the light we observe varies between 54.2° and 55.8° .

It is customary to parametrize the scattering function $S(\theta)$ of an astronomical source by a Heyney-Greenstein function of

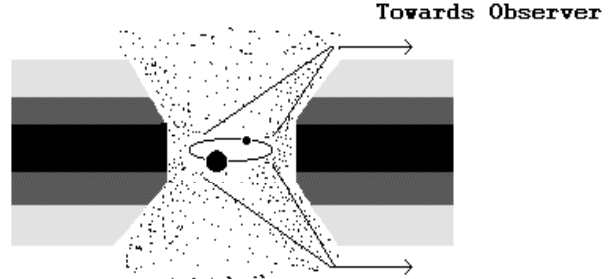


Fig. 3. A geometric model for the inner part of the Red Rectangle. Note that the thickness of the disk is two orders of magnitude larger than the size of the binary system. During the orbit, the scattering angle toward the observer varies, being largest at inferior conjunction, when minimum brightness is observed.

the form

$$S(\theta) = (1 - g^2)(1 + g^2 - 2g \cos \theta)^{-3/2}$$

Isotropic scattering corresponds to $g = 0$ and g approaches unity for strong forward scattering. In typical sources, g ranges between 0.6 and 0.8. For g values of 0.6, 0.7, and 0.8, the ratio of forward scattered light to that scattered at an angle of 55° varies by factors 8.6, 21.1, and 76.8, respectively; in the latter case, the brightness would be much lower than is observed, so that it appears likely that g falls in the range 0.6-0.7. The variable scattering angle then induces photometric variations with an amplitude between 0.067 and 0.076 mag. The observed amplitude of some 0.12 mag is slightly larger; nevertheless, the agreement with a model in which the scattering surface was assumed constant and no additional extinction variations were taken into account, is encouraging.

4. Evolutionary history of the system

The mass function of the spectroscopic binary is $0.049 M_\odot$. Assuming an ‘effective’ inclination of 35° , the mass of the unseen companion can be derived for various masses of the primary. For primary masses in the range between 0.56 and $0.80 M_\odot$, typical for post-AGB stars, the mass of the secondary falls in the range between 0.77 and $0.91 M_\odot$, i.e. masses well below the initial mass of the primary. It is then most natural to assume that the secondary is a low-mass main-sequence star.

The present orbital parameters of the system are such that no AGB star with the same luminosity can fit into the orbit. On the other hand, if Roche-lobe overflow had occurred on the AGB, it is dubious whether the system could have survived as a relatively wide binary. This problem is already encountered for HR 4049, whose orbital period is 429 days. It is even more severe in the case of HD 44179, because its orbit is shorter, and moreover the initial mass of the star was probably larger than for HR 4049. Nevertheless, the carbon richness of the nebula does suggest that the star has gone through the thermal pulses which normally occur near the end of AGB evolution.

The present characteristics of the Red Rectangle therefore suggest that filling of the Roche lobe was not necessary for

mass transfer to occur. Probably, then, mass loss started on the AGB before the Roche lobe has been filled, altering substantially the evolution of HD 44179. Apparently, this mass-loss process prevented the star from ever filling its Roche lobe, even during the thermally pulsing AGB. The luminosity may have increased at a normal rate, but the radius would be lower than for single AGB stars, i.e. the AGB evolution takes place on a track which is much bluer than for single stars.

It is then not at all clear whether the present envelope mass is as low as the 0.05 solar mass that is usually assumed at the start of a post-AGB evolutionary track. Indeed, in the scenario we propose, one may argue whether these stars can be called *post-AGB* stars. The present evolutionary timescale of HD 44179 could then be longer than for typical post-AGB stars. We note that a longer timescale is indeed more consistent with the huge extent and small outflow velocity of the nebula: from a coronagraphic picture taken at the ESO NTT, the extent of the nebula is some 40" on both sides; the expansion velocity, deduced from the CO lines, amounts to some 6 km/s (Jura et al. 1995); hence, an age of more than 10 000 years follows for the nebula, much longer than the typical post-AGB timescale. A very short evolutionary timescale seems unlikely also in view of the fact that not less than four such objects brighter than ninth magnitude are known.

Similar problems with orbital sizes are well known for the barium stars, which are binaries containing a white dwarf, which thus formerly was an AGB star. The overabundances of the s-process elements in the barium stars are interpreted as due to wind accretion from this AGB star. Also barium stars occur with orbital periods that are too short for normal AGB evolution. It has been suggested that the progenitors of these close barium stars have always remained detached, and that mass transfer occurred via wind accretion (Boffin & Jorissen 1988; Jorissen & Boffin 1992; Theuns & Jorissen 1993).

We suggest that HR 4049 and HD 44179 are progenitors of barium stars. Indeed, they are binaries with similar periods, the primary of which is presently finalizing its evolution before it becomes a planetary nebula and then a white dwarf. In our systems, the secondaries, that will later be seen as barium stars, are still on the main sequence. Important mass loss is presently observed, and it is likely that a fraction of it is captured by the companion.

Unfortunately, this suggestion cannot easily be checked directly. The companion is much too faint to detect the s-process elements it accreted after they had been produced during the thermal pulses of the primary. Only for one star of the group, the coolest member HD 52961, could the s-process elements Ba and Sr be detected in the spectrum of the primary: they follow the iron abundance rather closely, because also these elements have been absorbed by the dust and were not reaccreted.

Another peculiar characteristic which is shared by our systems and the short-period barium stars, is the fact that the orbits are eccentric, while one would expect that tidal interactions are very effective in circularizing the orbits. Here again, the substantial circumbinary disks these objects develop may yield the answer. Recent studies show that binaries may acquire their eccentricity through tidal interactions with the disks in which they are formed (Artymowicz et al. 1991). It is then natural to conjecture that the mass lost by HD 44179 and HR 4049, which appears to accumulate preferentially in a disk, finally increases the eccentricity rather than circularizing the orbit. If this conjecture proves true, it would strengthen the

link with the barium stars, because it would imply that a previous circumbinary disk must be invoked to explain the present eccentricities of barium stars in close binary systems.

Acknowledgements. The authors thank Drs. Henny Lamers, Alain Jorissen, and René Oudmaijer fruitful discussions. We thank the staff of Geneva Observatory for their generous awarding of telescope time at the Swiss Telescope at La Silla Observatory. We also thank Dr. Hugo Schwarz for his help for obtaining the coronagraphic image and Hans Plets for the fitting of the velocity curve. This work has been sponsored by the Belgian National Fund for Scientific Research, under grant No. 2.0145.94. LBFMW gratefully acknowledges support from the Royal Netherlands Academy of Arts and Sciences. EJB was supported by grant No. 782-371-040 by ASTRON, which receives funds from the Netherlands Organisation for the Advancement of Pure Research (NWO).

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